REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	14th September 2004	Final Progress 15 May 2002 – 15 August 2004

4. TITLE AND SUBTITLE
Employing Noisy Environments to Support Quantum Information Processing

5. FUNDING NUMBERS
DAAD19-02-1-0161

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
43371.7-PH-QC

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

In this project we have investigated the use of noise to support the generation of noise and coherent quantum information processing. We have presented schemes to this effect firstly in quantum optical settings (optical cavity QED, ion traps) and then in condensed matter environments (nano-mechanical oscillators and SQUID technologies). Abstract theoretical investigations into the usefulness of noise for quantum information processing have been carried out. The work on this project has led to 7 publications, of which 2 appeared in Physical Review Letters and one in PRA Rapid Commmunications. The work of this project has been presented in 17 talks at international conferences and university colloquiuae.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Quantum Information, Noise	4
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**

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Scientific accomplishements:

We have studied the dynamics of two trapped ions inside an optical cavity. This cavity may decay (which it will usually do at a rate in the MHz-GHz range). Due to the strong decay of the cavity mode any implementation of entanglement dynamics in such a system has to avoid populating the cavity mode. Here we achieve this my detuning the cavity mode strongly from the atomic transition. As a consequence transitions into the cavity modes rapidly dephase due to the detuning, however, this still leaves space for two-photon processes that only lead to a virtual population of the cavity mode. This is analogous to the way in which dipole-dipole interaction between closely spaced ions in free space emerges. However, due to the presence of the cavity this interaction is enhanced (despite the cavity decay) and the ions may be separated by many optical wavelengths. We have demonstrated that entanglement dynamics can be achieved in such a system. The results of this work have been published in E. Jané, M.B. Plenio and D. Jonathan, "Quantum Information Processing with trapped ions in far-detuned optical cavities" Phys. Rev. A Rap. Comm. 65, R50302 (2002).
In this work the origin of the dephasing of the transitions to the cavity mode is due to a strong detuning. However, it appears that the precise mechanism for this dephasing is not important.

We also studied novel approach for the robust generation of entanglement in atom-cavity systems. A paper entitled "Robust generation of entanglement between two cavities mediated by short interactions with an atom" has appeared in Phys. Rev. A 67, 012325 (2003).

We study whether it is possible to use white noise to generate entanglement between optical light modes. More specifically, we study an atom that couples to two distinct leaky optical cavities and is driven by an external optical white noise field. Surprisingly, it is indeed possible to generate entanglement between the light fields sustained by two optical cavities arises in such a situation. The entanglement is maximized for intermediate values of the cavity damping rates and the intensity of the white noise field, vanishing both for small and for large values of these parameters. This behaviour is reminiscient of the classical phenomenon of stochastic resonance where non-linear systems perform best when subjected to an intermediate amount of noise. It remains unclear to us at the moment whether there is a direct connection between the effects of classical stochastic resonance and the here demonstrated generation of entanglement by white noise. Nevertheless this example illustrates the possibility of generating entanglement by exclusively incoherent means and sheds new light on the constructive role noise may play in certain tasks of interest for quantum information processing.
This work has been published in M.B. Plenio and S.F. Huelga, "Entanglement from white noise," Phys. Rev. Lett. 88, 197901 (2002) and has been featured in Nature Physics Portal.

The demonstration of this effect could either be done in optical cavities or by replacing the optical cavities by motional degrees of freedom of a trapped ion. After the review meeting in Nashville this year the co-PI, Susana Huelga, has visited the group of Dave Wineland (NIST) to look discuss this and other work and in particular the possibility for replacing the optical cavities by motional degrees of freedom of a trapped ion. During a visit to the Perimeter Institute (Waterloo, Canada) we have also discussed the possible implementation of this effect in ion traps with Brian King who is now at McMaster University in Canada.

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We have investigated novel mechanisms in the generation and distribution of entanglement in arrays of nano-mechanical oscillators. While the standard approach to the generation of entanglement between distant sites requires significant amounts of spatial and temporal control our proposed method employs quantum fluctuations to produce significant amounts of entanglement over large distances without the need for detailed spatial and temporal control. This idea will appear in Physical Review Letters in October 2004. The propagation of entanglement in such systems will exhibit a resonance like structure favouring the transmission of an intermediate amount of entanglement. Again this form of propagation has very weak control requirements. These results have been published in M.B. Plenio, J. Hartley and J. Eisert, "Dynamics and manipulation of entanglement in coupled harmonic systems with many degrees of freedom" New. J. Phys. 6, 36 (2004).
While all experimental parameters suggest that it should be possible to generate these effects, the key obstacle will be the verification in such systems. Following recent exciting progress by Schwab the experimental detection schemes are now approximately a factor of 4 away from the required sensitivity (as compared to a factor of 100 that was valid 18 months ago).

We have established contact with Prof. Roukes (CalTech) and Prof Schwab (Maryland) who are leading experimentalist in this area to establish a contact with the view of exploring in more detail how our ideas may be impemented. Prof Schwab has visited us at Imperial College to discuss these schemes and the possibilities for their implementation in nano-mechanical oscillator systems.

We have investigated from an abstract point of view the concept of the use of noise to support coherent quantum information processing. In this context we have proven that a non-universal set of quantum gates that can be simulated efficiently on a classical computer (and is therefore useless for quantum computation) can be turned into a set of gates that is capable of universal and efficient quantum computation. This recent result, together with many considerations on noise thresholds in quantum computation, presented in S. Virmani, S.F. Huelga and M.B. Plenio, "Classical simulatability, entanglement breaking, and quantum computation thresholds." LANL e-print quant-ph/0408076 have been submitted for publication to Physical Review A.

Papers published in peer review journals:

1) E. Jané, M.B. Plenio and D. Jonathan, "Quantum Information Processing with trapped ions in far-detuned optical cavities" Phys. Rev. A Rap. Comm. 65, R50302 (2002).
2) M.B. Plenio and S.F. Huelga, "Entanglement from white noise," Phys. Rev. Lett. 88, 197901 (2002)
3) D. Browne and M.B. Plenio, "Robust generation of entanglement between two cavities mediated by short interactions with an atom", Phys. Rev. A 67, 012325 (2003).
4) D.E. Browne, M.B. Plenio and S.F. Huelga, 'Robust creation of entanglement between ions in spatially separate cavities', Phys. Rev. Lett. 91, 067901 (2003).
5) M.B. Plenio, J. Hartley and J. Eisert, 'Dynamics and manipulation of entanglement in coupled harmonic systems with many degrees of freedom', New Journal of Physics 6, 36 (2004)
6) J. Eisert, M.B. Plenio, S.Bose and J. Hartley, 'Towards mechanical entanglement in nano-electromechanical devices', to appear in Phys. Rev. Lett. 93, October 2004
7) S. Virmani, S.F. Huelga and M.B. Plenio, "Classical simulatability, entanglement breaking, and quantum computation thresholds." LANL e-print quant-ph/0408076

Talks presented on the subject of this proposal:

Martin Plenio: Entanglement in noisy environments, **Invited** Colloquium at the Technical University of Darmstadt, Germany, (Inv. Prof. G. Alber), 4th June 2002.

Susana Huelga: Entanglement in noisy environments, **Invited talk** The Perimeter Institute, Waterloo, Canada, (Inv. Prof. M. Mosca), 31st July 2002

Susana Huelga: Quantum Information processing supported by noise, **Invited talk** at the INAOE workshop on Modern Optics, Sta. María Tonantzintla, Puebla, Mexico, 2nd –13th September 2002.

Susana Huelga, "Quantum entanglement from white noise", 17th April 2003, **Invited talk** at the Perimeter Institute of Theoretical Physics, Waterloo, Canada

Susana Huelga, "Employing noisy environments to implement quantum information processing", 10th April 2003, **Invited talk** at the Department of Physics, University of Toronto, Toronto, Canada

Martin Plenio, "Entanglement from noisy environments" Invited talk at the SPIE conference 'Fluctuations and Noise in Photonics & Quantum Optics' in Santa Fe, USA, 1st – 4th June 2003.

Martin Plenio, "Employing noisy environments to support quantum information processing" Invited talk at the 'Quantum Computing Review Meeting' in Nashville, USA, 18th – 22nd August 2003

Susana Huelga, "Entanglement Generation and Quantum Networking in Cavity QED" **Invited talk** at the EuroConference on Cavity QED and Quantum Fluctuations: From Fundamental Concepts to Nano-Technology, Granada, Spain, 28th September 2003.

Martin Plenio, "Entanglement in noisy environments: Making it or breaking it." **Invited talk** at the QuAMP Workshop on Quantum Information Processing in Milton Keynes, UK, 7th – 12th September 2003.

Martin Plenio, "Entanglement in noisy environments: Making it or breaking it." **Invited talk** at the "Laser Science XIX annual meeting co-located with the 87th OSA annual meeting Frontiers in Optics", Tucson, USA, 5th – 9th October 2003.

Martin Plenio, "Entanglement in noisy environments: Making it or breaking it." **Invited talk** at the University of Kaiserslautern, Germany, 28th October 2003

Martin Plenio, "Novel modes for the generation, manipulation and propagation of entanglement over short distances" **Invited talk** at the Start-up meeting of the QIP-IRC, Oxford 8-9th January 2004.

Martin Plenio, "Entanglement in interacting quantum systems: Statics, Dynamics and Implementations", **Invited talk** at the Max-Planck Institute for Quantum Optics, Garching Germany 3rd February 2004.

Martin Plenio, Entanglement in interacting quantum systems: Statics, Dynamics and Implementations, **Invited talk** 3rd Workshop on Continuous-Variable Quantum Information Processing (CVQIP'04), Erlangen, Germany, 2nd – 5th April 2004. (Presented by Plenio)

Martin Plenio, "Entanglement in interacting quantum systems: Statics, Dynamics and Implementations." **Invited talk** at the University of Cambridge, (Inv. Prof. Khmelnitskii), 26th February 2004

Martin Plenio, "Entanglement in interacting quantum systems: Statics, Dynamics and Implementations." **Invited talk** at the University of Nottingham, (Inv. Prof. Belavkin), 17th March 2004.

Martin Plenio, "Entanglement in interacting quantum systems: Statics, Dynamics and Implementations", **Invited talk** 3rd Workshop on Continuous-Variable Quantum Information Processing (CVQIP'04), Erlangen, Germany, 2nd – 5th April 2004

The principal Investigator, Prof. Martin Plenio, has been awarded the Maxwell Medal and Prize of the Institute of Physics (equivalent of the APS) for the year 2004. "For his influential

contributions to quantum information theory, in particular the characterization and manipulation of quantum entanglement and its application to the processing of information."

Prof Plenio has also been elected a Fellow of the Institute of Physics (equivalent of APS).

Scientific Personel:
Shashank Virmani served as postdoc of the project for the first year at Imperial College and the second year at the Univeristy of Hertfordshire.

Report of Inventions:
N/A

Technology transfer:
N/A